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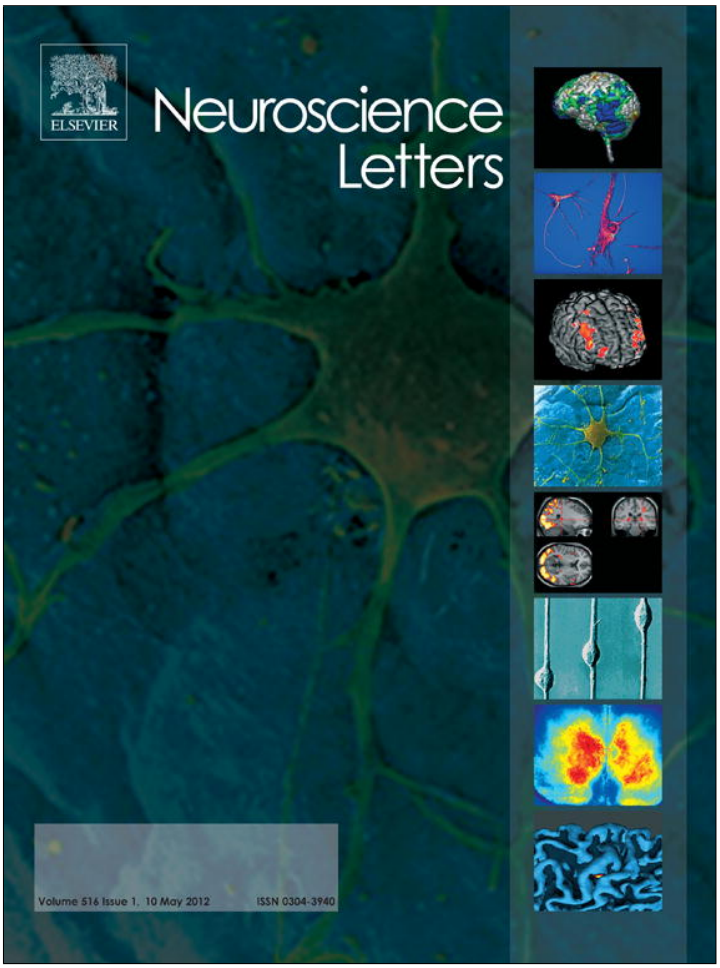

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Experimental simulation of the effects of sudden increases in geomagnetic activity upon quantitative measures of human brain activity: Validation of correlational studies

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ABSTRACT

Previous correlations between geomagnetic activity and quantitative changes in electroencephalographic power revealed particular associations with the right parietal lobe for theta activity and the right frontal region for gamma activity. In the present experiment subjects were exposed to either no field (sham conditions) or to either 20 nT or 70 nT, 7 Hz, amplitude modulated (mHz range) magnetic fields for 30 min. Quantitative electroencephalographic (QEEG) measurements were completed before, during, and after the field exposures. After about 10 min of exposure theta power over the right parietal region was enhanced for the 20 nT exposure but suppressed for the 70 nT exposure relative to sham field exposures. The effect dissipated by the end of the exposure. These results support the contention that magnetic field fluctuations were primarily responsible for the significant geomagnetic–QEEG correlations reported in several studies.

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Several tens of studies [see [13] for a review] have shown moderate strength correlations ($rs = \sim 0.4 \pm 0.1$) between increases in geomagnetic activity and various behavioral inferences of cerebral activity. When global geomagnetic variation intensities exceed aa (average antipodal) values of about 20 nT there are increased incidences of convulsive activities [22], post-mortem hallucinations [15,23], vestibular experiences [16] in human beings and enhanced mortality in rats with acute epileptic limbic activity [6]. The latter can be simulated by experimentally applied 7 Hz magnetic fields with peak intensities of 40 nT but not 100 nT [17].

Michon and Persinger [12] found that the same effect size (*i.e.*, the amount of variance explained) for the correlation between geomagnetic activity and spontaneous seizures in chronic epileptic rats [18] could be produced by whole body application of 7 Hz amplitude modulated magnetic fields in successive steps from 1 nT to approximately 50 nT every 3 min (~5.6 mHz) for 2 h. The 7–8 Hz fundamental pattern has been considered relevant [7] because it matches the fundamental value for the earth-ionospheric Schumann resonance and has been found as a central component of background geomagnetic activity [8]. As shown by Koenig et al. [9] all of the fundamental frequencies noted in electroencephalographic patterns are also produced within the earth-ionospheric cavity.

Babayev and Allahverdiyeva [2] found that reliable qualitative changes in electroencephalographic (EEG) activity in normal people occurred during severe geomagnetic disturbances. Using quantitative EEG (QEEG) Mulligan et al. [14] confirmed that significant alterations in theta (4–7 Hz) over the parietal and gamma range (>35 Hz) power over the prefrontal region were correlated with daily geomagnetic activity within a narrower and less intense range than those reported by Babayev and Allahverdiyeva [2]. The power spectra within the right hemisphere were more affected than the left. Because both studies were correlational, we designed an experimental simulation of one component of geomagnetic activity that was applied while QEEG measurements were recorded.

We selected repeated 6 min sequences of 7 Hz amplitude-modulated patterns with either 0 nT (sham) 20 nT or 70 nT peak intensities. The duration was based on the average time of sudden storm commencements [10]. The amplitude modulation pattern, which contained components and subcomponents within the mHz range, is typical of geomagnetic power densities. The effectiveness of this particular pattern for producing electrical lability in rodents with histories of chemically-induced epilepsy has been shown [12].

On the bases of the estimated effect size we reasoned the expected statistically significant differences should be evident at the $P < 0.05$ level even with a small sample size of only 4 subjects

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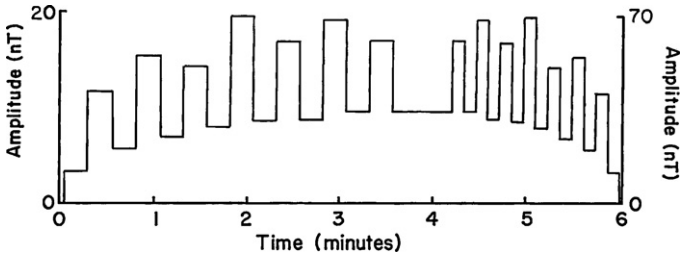

Fig. 1. The pattern of amplitude changes over the 6 min simulation of a sudden storm commencement. The pattern was identical for the two conditions except the absolute maximum intensity averaged either 20 nT or 70 nT in the volume occupied by the participants.

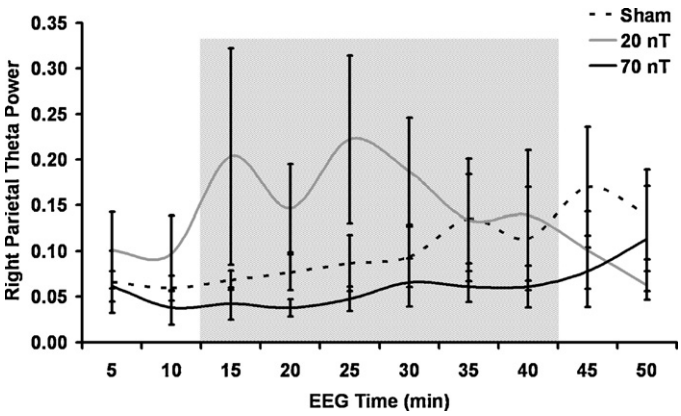

Fig. 2. Sequential 5-min means (±SEM) of right parietal theta EEG power over time for sham, 20 nT and 70 nT magnetic field treatments. Field exposure period is indicated by the grey quadrangle.

per treatment group. The protocol was approved by the university's Research Ethics Board. A total of 12 young (20–28 years of age) subjects (4, equal numbers of men and women, per treatment group) volunteered and were randomly assigned to the treatments: sham, 20 nT, or 70 nT conditions. To minimize effects due to environmental variability, all data collection was completed within a single month (5–29 November 2010).

Subjects were seated in a comfortable chair within an acoustically-shielded chamber (Faraday cage) described elsewhere [19]. The chair was located equidistant between 2 coils separated by 1 m. The coils were made from 70 turns each of 30 AWG wire wrapped around two racks of 1.2 m^2, and have been used in previous studies [12]. Each coil had a resistance of about 115 Ω. The coils were interfaced with a DOS-based PC (personal computer) through a custom-constructed digital-to-analog (DAC) converter. The PC-DAC apparatus was located outside the chamber.

The PC was equipped with custom software (Complex2) used to generate the simulated geomagnetic storm by converting a column of numbers (each value between 0 and 256) into voltages (±5 V) that were then applied through the coils as electric current. The point duration (duration of each successive voltage presentation) for each of the 5072 points was 69 ms. A single cycle lasted about 5 min and 50 s. The magnetic field pattern ran for 5 cycles. Peak-to-peak intensities of the field strength in the area occupied by the upper legs, torso and head of the subjects were measured by a commercial power meter. Detailed profiles for background, sham, 20 nT and 70 nT field conditions were obtained by further measurement (steady-state displacement) with a triaxial fluxgate magnetometer (model FM-300, MEDA, Dulles, VA). The shape of the amplitude modulation of the intensity during each 6 min sequence is shown in Fig. 1.

Subjects wore a 19-channel EEG sensor cap (Electro-Cap International, Eaton, Ohio). Sensor impedances were checked and maintained below 20 kΩ for the duration of the procedure. EEG signals were amplified (Mitsar EEG model 201, Saint Petersburg, Russia) and recorded on a laptop (WinEEG software) located outside the chamber. Before the chamber door was closed subjects were told to sit quietly and that they may or may not receive weak magnetic fields as specified in the consent form. A lapel microphone and speaker system was available for any urgent communication between the subject and experimenter. After the chamber doors were closed, EEG data collection began and proceeded undisturbed for a total of approximately 50 min.

After 10 min of recording subjects were unknowingly presented with 5 sequential cycles of the simulated sudden (geomagnetic) storm commencements (total duration = 29 min 17 s) at one of 3 peak flux densities: <1 nT (sham), 20 nT or 70 nT. The intensity condition for each subject was assigned based on a randomized order. The field exposure was followed by another 10 min of EEG recording. Field on- and off-sets were indicated on the electronic EEG record.

Monopolar (bilateral ear lobe referenced) 19-channel EEG records (sampled at 500 Hz) were split into 1-s epochs. Spectral power values for delta (1–4 Hz), theta (4–8 Hz), low-alpha (8–10.5 Hz), high-alpha (10.5–13 Hz), beta (13–35 Hz) and gamma (35–45 Hz) bands were generated for 8 International 10-20 scalp sensor positions (F7, F8, T3, T4, P3, P4, O1, O2) with MatLab (version 6.5). These bands and scalp positions were selected based on previous correlational research [14]. The same clinical bands employed in the correlational study were also used here. Power values were exported to SPSS for Windows (version 17) for analysis. Spectral power scores derived from 1-s EEG epochs were sequentially grouped into 5-min blocks. Consequently there were 2 time blocks representing the 10 min of pre-magnetic field measurement, 6 blocks representing the 30 min of field exposure, and a final 2 blocks for post-field measurement.

Scores from 1-s EEG epochs contaminated by movement artifacts were excluded and the remaining artifact-free epochs were used to calculate 5-min means for each frequency band at each sensor position. The mean (standard deviation in parentheses) numbers of 1-s epochs used to generate the mean power scores for each of the successive 5-min blocks was 287.9 (26.4). For each set of 6 frequency bands the primary analysis was a MANOVA comprised of 10 sequential blocks of time (2 baseline, 6 field exposure, 2 post-field), 4 lobes (frontal, temporal, parietal, occipital), 2 hemispheres (left, right) and 6 spectral bands across 3 independent magnetic field intensity conditions (sham, 20, 70 nT).

Although there were no statistically significant effects of the applied magnetic field for right frontal, temporal or parietal gamma, or for right frontal or temporal theta (all $F_{(4,18)} < 2.860$, all $P > 0.15$), right parietal theta showed the predicted interaction ($F_{(4,18)} = 4.241$, $P < 0.05$; one-tailed test) for applied magnetic field intensity by 5-min time blocks of EEG recording (Fig. 2).

Post hoc analysis indicated that the mean power over the right parietal region for the 20 nT group was significantly greater than that of the sham group after 5 and 15 min of magnetic field exposure (15 and 25 min, respectively, of elapsed EEG recording time), while the mean for the 70 nT group was significantly suppressed relative to sham after 10 min of magnetic field exposure (20 min elapsed EEG recording time). Power was not different for the 10 min prior to magnetic field treatment and all between-group differences attenuated after 15 or 20 min of field exposure.

The results of this experimental simulation of a "sudden commencement" mHz range amplitude modulation of 7 Hz magnetic fields showed that *theta* activity in the right parietal region was increased for the 20 nT exposures but dampened for the 70 nT intensities compared to sham field controls. In our correlation

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study [14] the two frequency bands most consistently correlated with increased global geomagnetic activity were theta (4–7 Hz) and gamma (35–45 Hz) activity. The enhanced QEEG power during exposure to the experimental magnetic fields was not immediate, which eliminates the likelihood of a direct induction artifact, but required about 5–10 min to emerge and had dissipated after 20 min of exposure. Such latencies for electroencephalographic responses to weak magnetic fields within the nT to 1 μT range have been shown in several other studies with different application geometries [16,17,20]. That ~1 μT, 60 Hz magnetic fields can affect a variety of enzyme systems *in vitro* has been shown by Blank and Goodman [5].

The major effect for the 20 nT variations occurred over the right parietal lobe which is similar to the results of our [14] correlation analyses with a larger sample size. In that study 20–40% of the shared variance between increased geomagnetic activity (0–70 nT; mean about 25 nT) in EEG power for both multiple and repeated single-subject studies was localized positively with the right parietal region for theta power and negatively with the frontal region for gamma power.

The experimental fields in this study did not significantly affect the gamma power over the right frontal region. We suggest that the component of normal geomagnetic activity that was responsible for right parietal region-theta effect was not simulated in our experimental configuration for the right frontal region. We expect that a 40 Hz "ripple" would be more effective on the bases of the predominance of gamma activity over this region. Right frontal–parietal regions are so intricately connected that damage to the right parietal lobe frequently results in clinical profiles that are very difficult to distinguish from right prefrontal injuries. That individuals with histories of brain injuries are sensitive to 20–50 nT experimental 7 Hz magnetic fields and comparable intensities of geomagnetic activity has been reported recently [24].

Few studies have examined EEG outcomes from application of time-varying magnetic fields applied to the whole body with dominant frequencies of 10 Hz or less [25]. One research group conducted two studies [3,4] using the same 1.5 Hz and 10 Hz magnetic fields but applied the fields at two different intensities (100 μT *vs.* 10 μT) about a thousand times more intense than the ones employed in the present study. Both treatments resulted in significant changes in EEG power isolated to the frequency of stimulation. The higher intensity application (100 μT) produced a frequency-specific EEG power suppression [3], while the lower intensity treatment (10 μT) resulted in an enhancement of EEG power at the same frequency. Marino et al. [11] have reviewed the effects of power frequency magnetic fields upon the EEG profiles for human subjects.

The physiological mechanisms by which 7–8 Hz magnetic field oscillations could affect brain function have ranged from attributions to the consequences of evolution of life within the earth's Schumann resonance to intrinsic features of membrane time constants. We suggest another potential mechanism derived from the relationship between the intrinsic energy of patterns of neuronal activity and the information. According to Alonso and Klink [1] a conspicuous "subthreshold" of ~8 Hz, 2.5 mV oscillations occurs in layers II and III of the entorhinal cortices. It is relevant that this region, particularly within the right hemisphere, is a major integrator of information between the hippocampal formation and neocortices with specific inputs to the parietal and prefrontal cortices.

The Landauer "limit" occurs when an informational bit is dissipated during the merging of two computational pathways and is associated with the release of energy into entropy in the amount $kT \ln 2$, where k is the Boltzmann constant and T is the temperature. For a biological system at 37 °C the quantum of energy is $\sim 3.4 \times 10^{-21}$ J which is the same value as the energy equivalence from 2.6 mV on a net charge (1.6×10^{-19} A s) with a frequency [21] of about 8 Hz and suggests that the boundary between stochastic resonance and the kT threshold might mediate a potential geomagnetic-electroencephalographic interaction.

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